# The Impacts of Heating Actuators in Extremely Cold Space Environments

*NASA Glenn Research Center*

**Dr. Justin Scheidler**

Materials & Structures Division
Rotating & Drive Systems Branch

**Erik Stalcup**

Propulsion Division
Thermal Systems and Transport Processes Branch

**Dr. Erica Montbach**

Space Technology Project Office





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# Motivation

- Rotational actuators for Space mechanisms require a mechanical gearbox to meet mass, volume requirements
- Mechanical gears require lubrication to achieve satisfactory performance & life
- SOA approaches for temperatures < about -60 ºC:

| Current approaches | Current penalty |
|---|---|
| Heat the gearbox/motor to ≥ -60 °C & use grease lubrication | Increased complexity & mass<br>less power for science |
| Use dry film lubricant on contacting surfaces | (often significant) reductions in life<br>design constraints on load & speed |

- **This is a pervasive problem** – *potential for big impact*

| Mechanisms affected |
|---|
| Rover wheels |
| Solar arrays |
| Gimbals |
| ISRU (drills, buckets, etc) |
| Robot arms |
| … |

| Environments affected |
|---|
| Lunar surface |
| Lunar Gateway |
| Mars |
| Europa |
| Titan |
| … |

# Motors for Dusty & Extremely Cold Environments (MDECE) Project

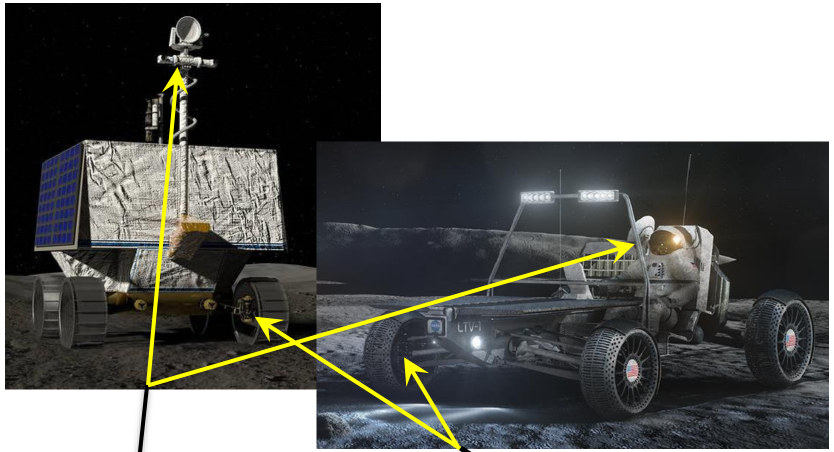
- **Research project, FY21 – FY24**
- **Goal:** Develop two <u>unheated</u> rotational actuators that can operate for a <u>long duration in extreme cold</u> (ambient temperature of -243 ºC (30 K))
  - Evaluate life in controlled, reproducible, representative lunar dust environment
- **Approach:** eliminate gearbox lubrication
  1 actuator with non-contact gearing; 1 actuator with no gears
- **Relevant environment:** Broadly applicable, but focusing on lunar permanently shadowed region (PSR)
- **Scope:**

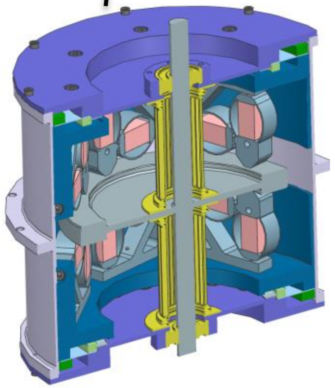
<u>In scope</u>
- Dust effects on actuator internals
  - Functional / active components
  - Dry film lubricant
- Compatibility with drive/controller
- Drive/controller development [piezo motor only]

<u>Out of scope</u>
- Bearings
- Dust seals
- Stand-alone dust mitigation tech

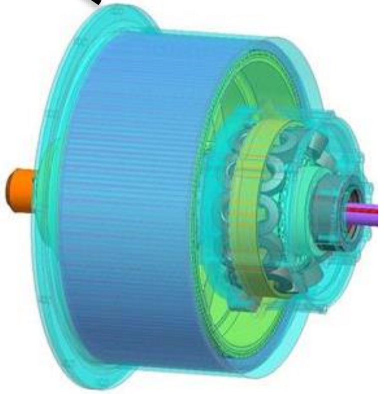
- **Promising applications:**
  - <u>Magnetic actuator</u>: rover mobility ▪ in-situ resource utilization ▪ robotic arm joints ▪ rotors for powered flight
  - <u>Piezoelectric actuator</u>: precision pointing (e.g., laser communication) ▪ low power robotic arm joints

Example mechanisms for demonstrating prototypes (NASA KSC)





Piezoelectric motor configuration 1 (JPL)
[ graphic courtesy of NDEAA team/JPL/Caltech/NASA (Patent pending) ]



Magnetically-geared motor concept (NASA GRC & GSFC)

# Heating Requirements in a Lunar PSR

**Objectives**

1. Quantify the energy required to heat a reference actuator from its survival temperature to its operating temperature (213 K)
2. Quantify the heater power required to maintain the reference actuator at 213 K

**Reference actuator:** 22 W continuous output, Ø97 mm x 169 mm cylinder with a mass of 3.15 kg

- Temperature-dependent heat capacity of Ti6Al4V
- Constant emissivity

**Lunar surface environment:** regolith temperature (30 K) & emissivity (0.95)

**Thermal model**

- Radiative heat transfer only
- No external heat sources (e.g., nearby hardware, reflected solar flux, Earthshine)
- 50% view factor to lunar regolith & to deep space

# Heating Requirements in a Lunar PSR

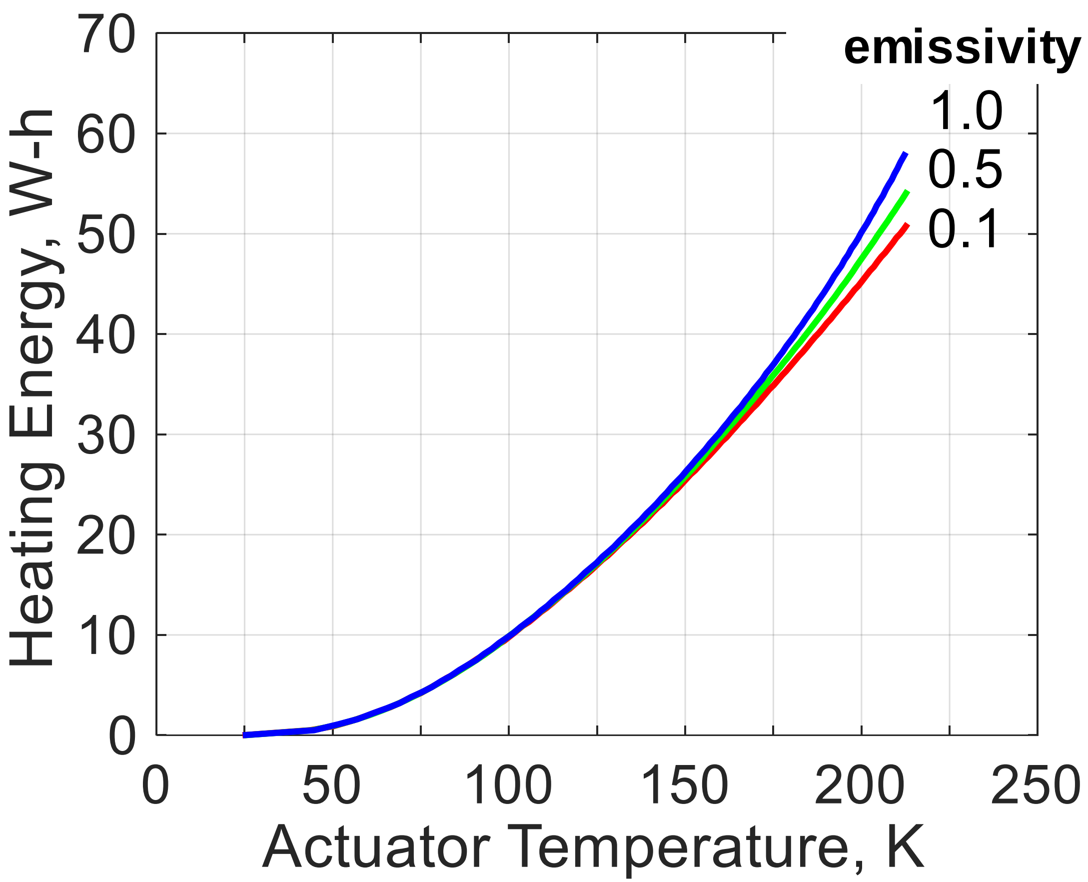
**Warmup heating energy** (transient analysis)

- Warmup heating power (17.0 to 19.4 W) calculated to provide 3 hour warmup time for each emissivity case
- Emissivity has small effect: sensible heat >> heat loss over 'short' time scale
  - Effect would be even smaller if shorter warmup time used

**Heating requirement to reach 213 K**
**(approx. start of grease lubrication regime)**

| Actuator emissivity | Warmup heating energy (W-h) |
|---|---|
| 0.1 | 51.0 |
| 0.5 | 54.3 |
| 1.0 | 58.1 |

**Heating energy required to reach a given temperature for different emissivities**

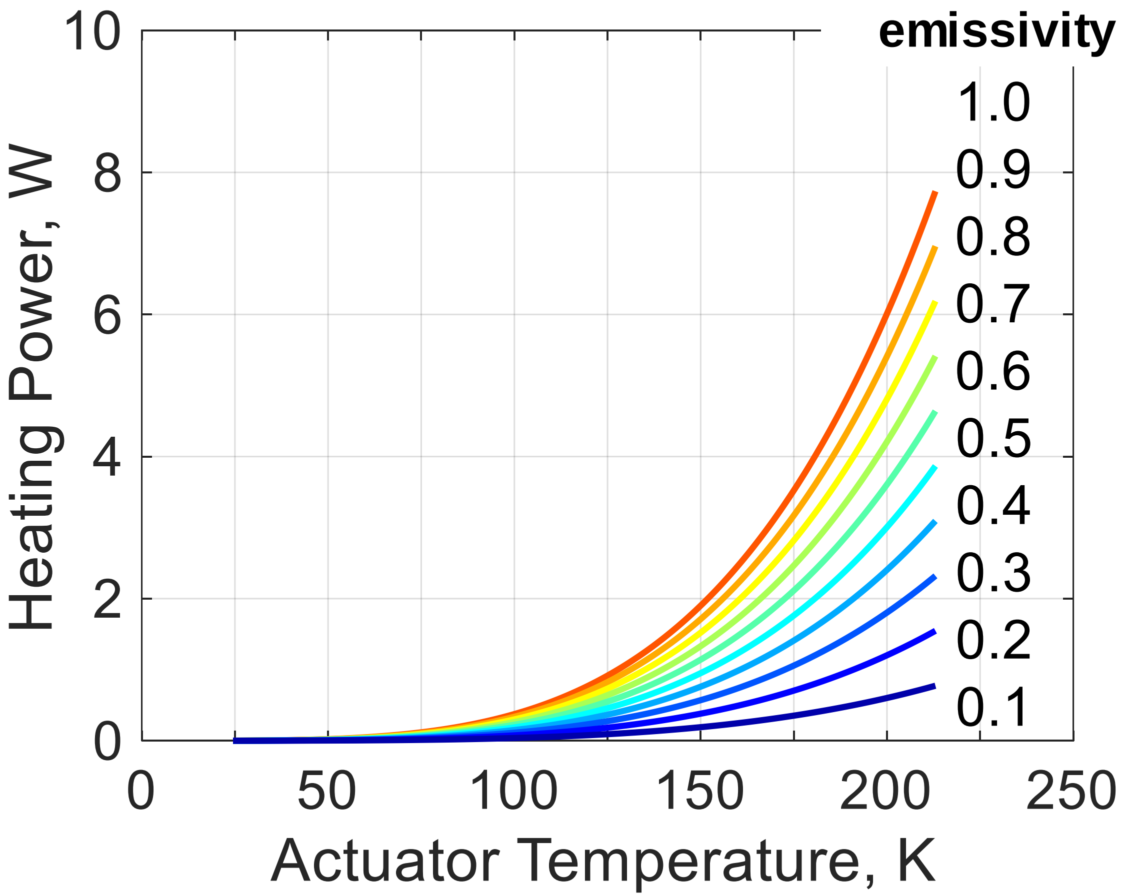


# Heating Requirements in a Lunar PSR

**Maintenance heater power** (steady state analysis)

- Emissivity has significant, linear effect
- Even for very small, continuous heating power (from inefficiency or dedicated heater), actuator will operate well above temperature of regolith

**Heating power required to maintain a given temperature for different emissivities**




**Heating requirement to operate at 213 K**
**(approx. start of grease lubrication regime)**

| Actuator emissivity | Maintenance heater power (W) |
|---|---|
| 0.1 | 0.8 |
| 0.5 | 3.9 |
| 1.0 | 7.8 |

# New Metric for Quantifying Impact of Heating Actuators

**Current practice:** report required heater power, heating duration, total energy, and/or mass of the heating system

- **Problem:** all extrinsic quantities (understanding of typical power, energy, & mass budgets is required for the scale of actuator and system in question)

New, intrinsic metric termed 'average total efficiency'

$$\eta_{avg}(t) = \frac{1}{t}\int_0^t \frac{P_{out}(t)}{P_{total\ in}(t)}\,dt$$

where

$P_{total\ in}$ = heater power + input electrical power to produce output torque

simplifies to →

Total mechanical energy output

$$\eta_{avg}(t) = \frac{E_{out}(t)}{E_{heater}(t) + E_{in}(t)}$$

Total energy consumed by heater

Total electrical energy input to produce torque

- As required heating decreases to 0, metric reduces to average value of conventional operating efficiency of actuator (i.e., datasheet efficiency)

# Case 1: Continuous Operation after Heating from Survival

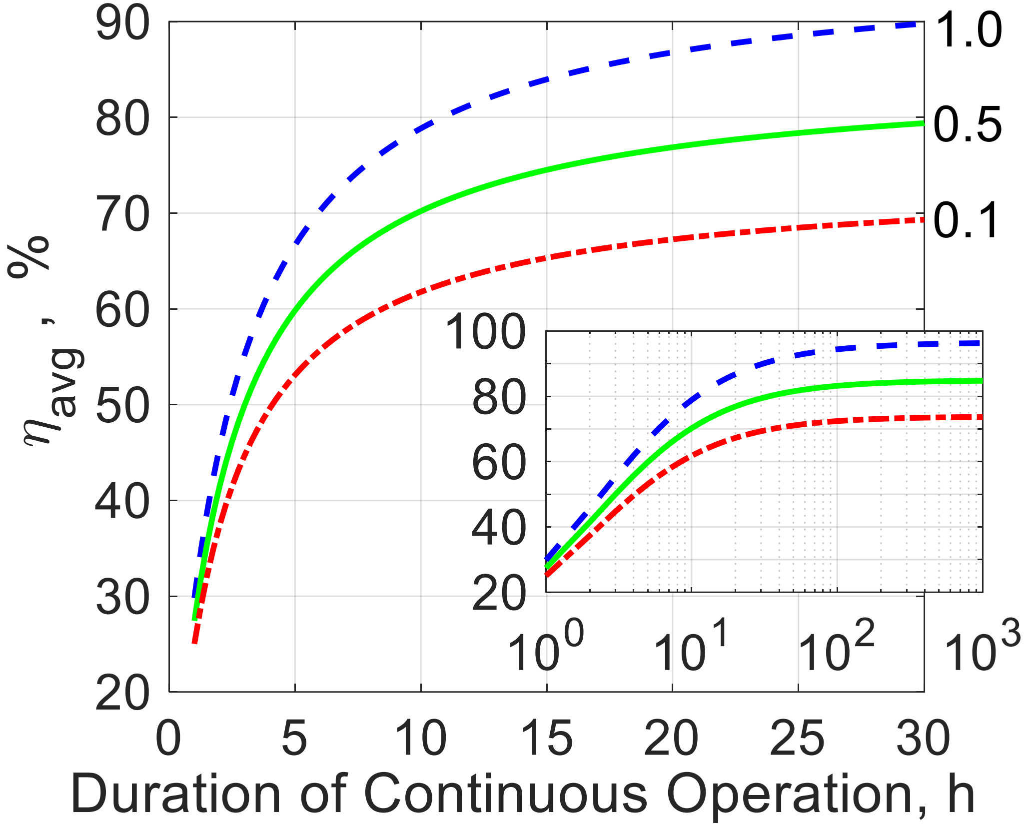
**Case 1 Con-Ops**

1. Heat the actuator from a cold survival state (30 K regolith, ~24.5 K actuator) to the minimum temperature for grease lubrication to function (213 K [-60 ºC])
2. Continuously operate the actuator for a finite duration under at constant, full power

**Best case scenario considered:** actuator's conventional operating efficiency is 100%

- Total power dissipated inside actuator is minimized (equals maintenance heater power)

**Change in average total efficiency over time for different emissivities**

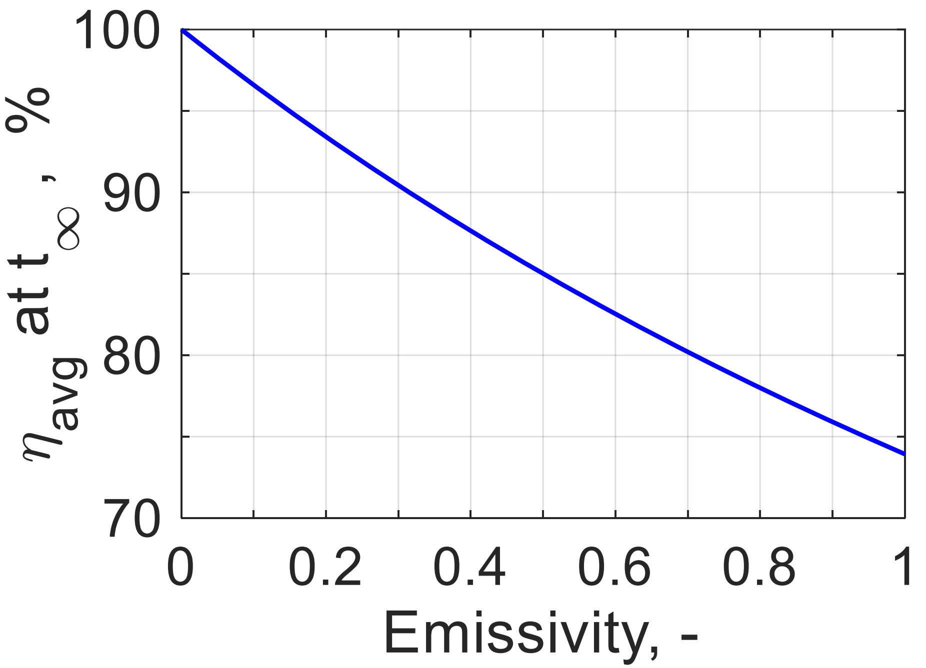



**Average total efficiency…**

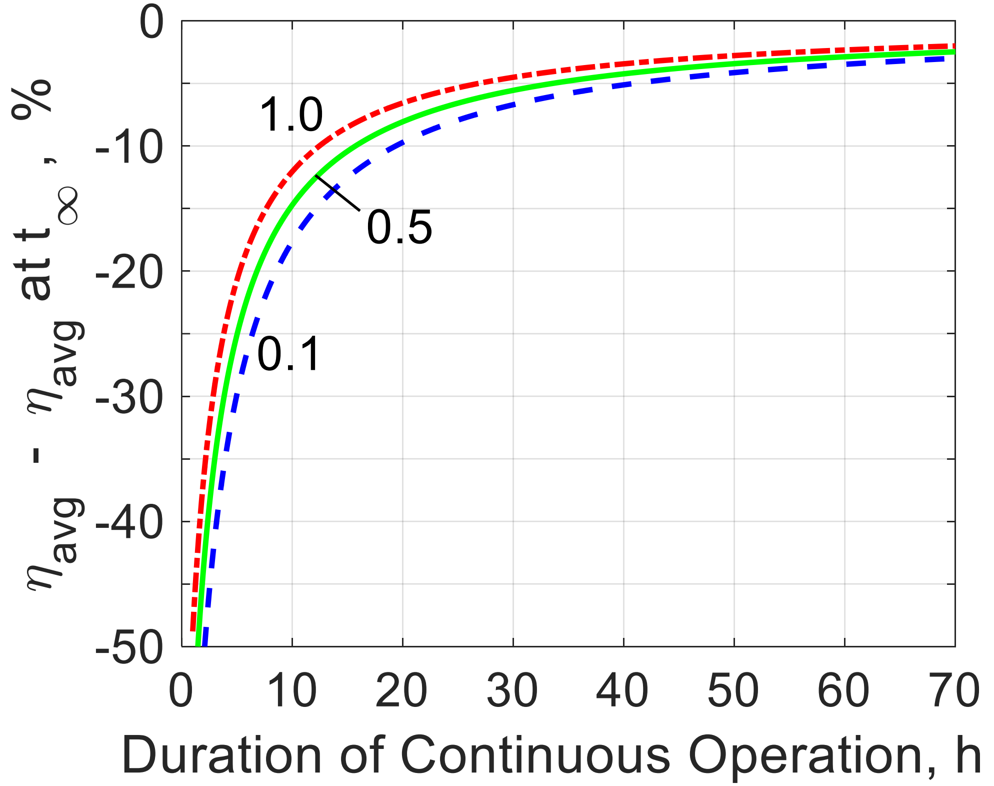
- Starts at 0% and remains low for multiple hours of continuous operation
- Never reaches 100%, even for continuous operation of an actuator with conventional efficiency of 100%

# Case 1: Continuous Operation after Heating from Survival

**Maximum possible average total efficiency for continuous operation**




**Average total efficiency relative to maximum possible value for different emissivities**




**For continuous operation…**

- Maximum possible average total efficiency is lower when emissivity is higher & can be < 75%
- It takes 12-19 hours to come within 10% of maximum possible average total efficiency & 27-41 hours to come within 5% of it

# Case 2: Long Duration Operation with Constant Duty Cycle

**Case 2 Con-Ops**

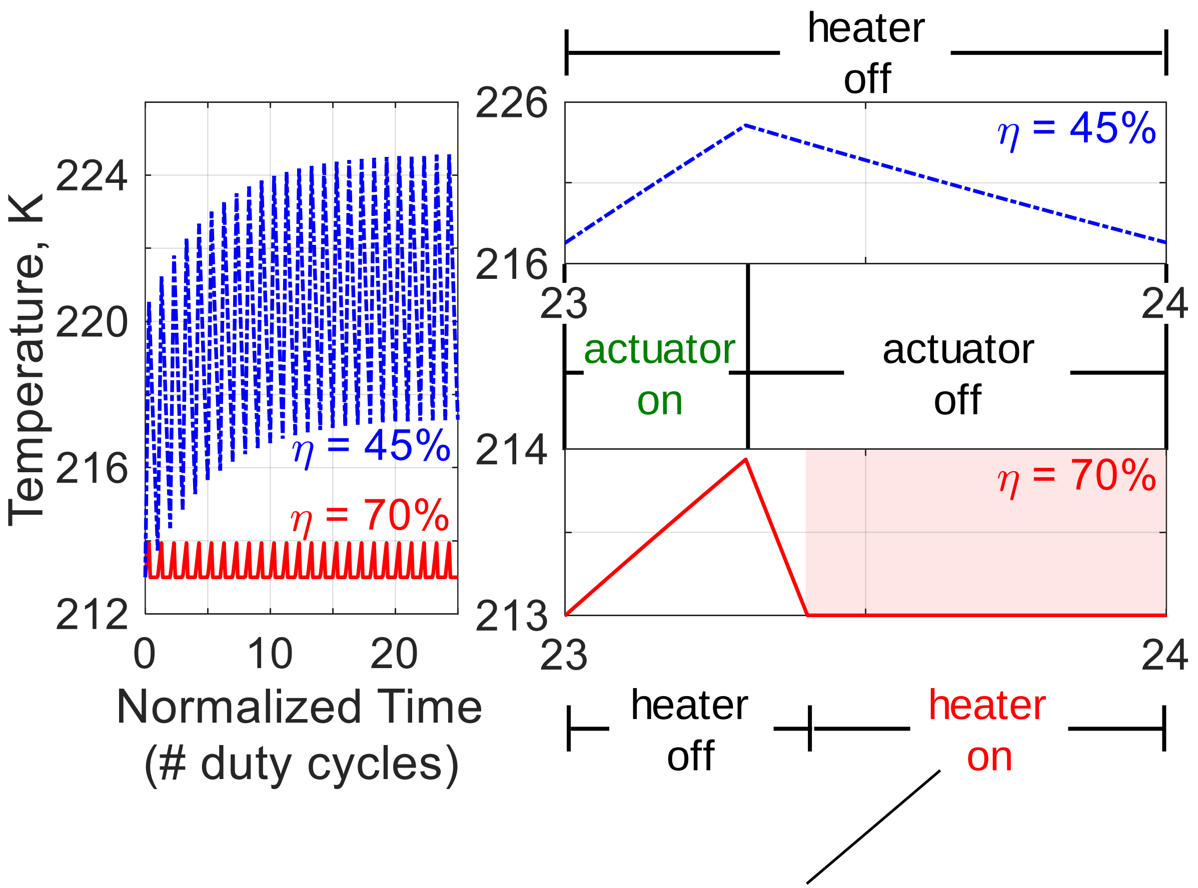
1. Heat the actuator from a survival state as in case 1
2. Operate the actuator at full power with a fixed duty cycle for a very long duration (full lunar night or longer)

**Duty cycle =** percent of time the actuator is excited (i.e., generating torque) while in an operating state

**Different conventional efficiencies considered**

- Transient analysis needed to determine if and for how long supplementary heating is required
- Actuator with low conventional efficiency may produce enough self heating to maintain its temperature at or above 213 K without supplementary heating

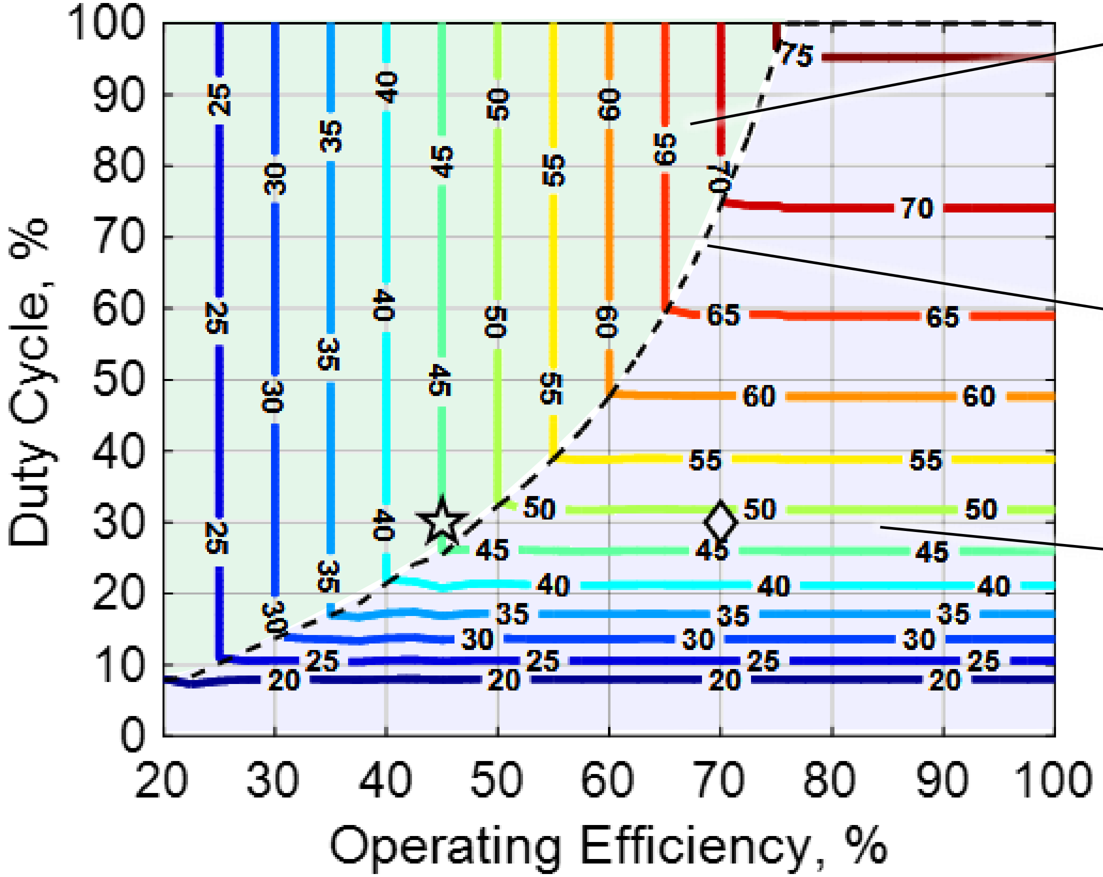
**Example temperature profiles at 30% duty cycle for an emissivity of 0.9 & operating efficiencies of 45% and 70%**




$$P_{heater} = P_{maintenance} - P_{loss}$$

# Case 2: Long Duration Operation with Constant Duty Cycle

**Average total efficiency contours for an emissivity of 0.9**




**Green region** – sufficient heat produced by inefficiency during operation

- No supplementary heat
- Average total efficiency = operating efficiency

**Dashed curve** – defines minimum duty cycle for which supplementary heating avoided

**Blue region** – insufficient self heat

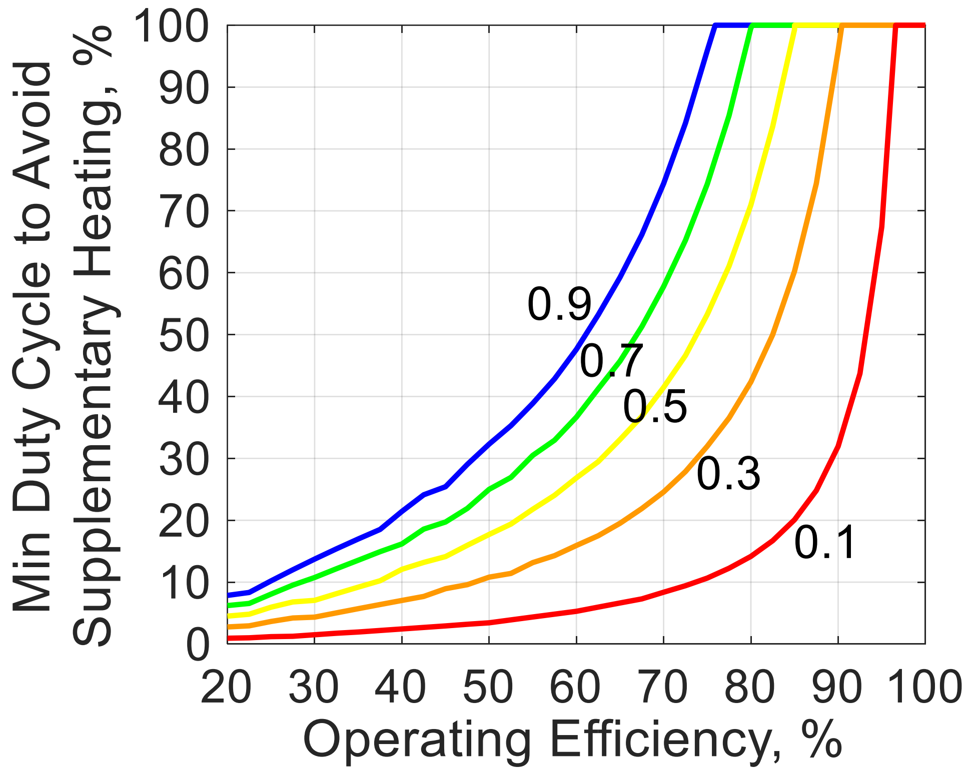
- Heater required
- Average total efficiency dictated by duty cycle (amount of work output) & required maintenance heater power

**For duty cycle operation…**

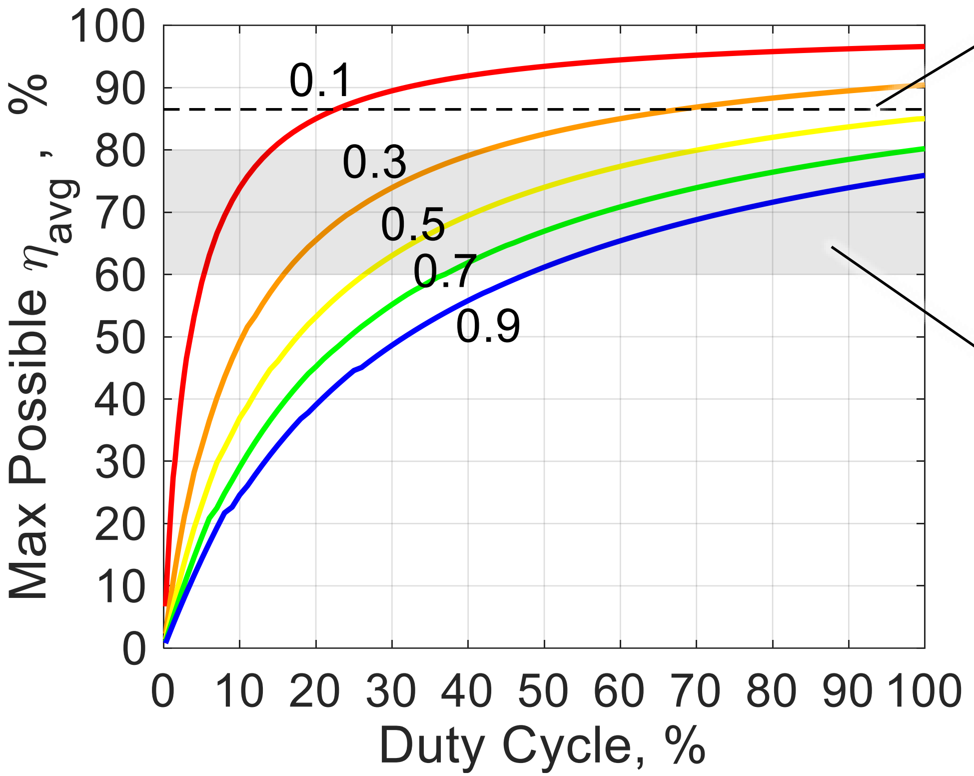
- Duty cycle must exceed a threshold to avoid supplementary heating
- Increased operating efficiency only helps when duty cycle exceeds its threshold

# Case 2: Long Duration Operation with Constant Duty Cycle

**Duty cycle threshold for avoiding supplementary heating for different emissivities (cannot be avoided when threshold = 100%)**




**Maximum possible average total efficiency for duty cycle operation & different emissivities**




**Dashed line** – Current best estimate of MDECE magnetic actuator's efficiency

**Gray region** – MDECE magnetic actuator key performance parameters for efficiency

**For duty cycle operation…**

- A lower emissivity (i.e., lower radiative heat loss) enables heater-free operation at a lower duty cycle
- A lower emissivity enables a higher limit on average total efficiency for any duty cycle

# Summary

- *Grease-lubricated* actuators can only operate above about 213 K (-60 ºC)
  - NASA's Motors for Dusty & Extremely Cold Environments **(MDECE) Project is developing 2 actuators that can operate down to 30 K without supplemental heating**
- The impacts of heating *grease-lubricated* actuators has historically been assessed using extrinsic metrics that are difficult to interpret
  - This paper explored the impacts using a **new, intrinsic metric** – average total efficiency – that describes the efficiency perceived by the system containing the actuator
- Calculated the heater energy required to warm up a **22 W, 3.15 kg reference actuator** from a survival state to 213 K and the heater power required to maintain 213 K
  - **Permanently shadowed lunar surface environment**: 30 K lunar regolith
- Trends in average total efficiency evaluated for **2 concepts of operation**
  - Short duration (< about 100 hours), continuous operation after heating from survival
  - Long duration (> about 100 hours) operation with constant duty cycle after heating from survival

# Key Conclusions

- Heating actuators reduces the power, energy, and time available for science and can necessitate a larger, heavier power source
- Even if the actuator has a conventional operating efficiency of 100%, the average total efficiency can be significantly lower (down to around 10%) in practical situations
- Average total efficiency is lowest for actuators with high emissivity operating at lower duty cycles for durations less than 10 hours
- Even when the penalty of initially heating the actuator is negligible (i.e., when it is operated for a very long duration), the average total efficiency can never exceed an upper limit that is < 100%
    - This limit is dramatically different (from around 15% to around 90%) for different actuator designs (choices of emissivity) and applications (duty cycle requirements)
- Due to heating requirements, a variety of missions will see no benefit to using a conventional actuator that is highly efficient under ambient conditions
- The impact of heating can be greatly reduced for all applications except those that demand duty cycles less than 10% by designing the actuator to have a very low emissivity (about 0.1 or less)
    - Such a design is likely impractical when the actuator must also be operated in regions with more moderate temperature or exposure to solar radiation

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# Contact Info

**Dr. Justin Scheidler** justin.j.scheidler@nasa.gov

Erik Stalcup erik.j.stalcup@nasa.gov

Erica Montbach erica.n.montbach@nasa.gov

# THANK YOU


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